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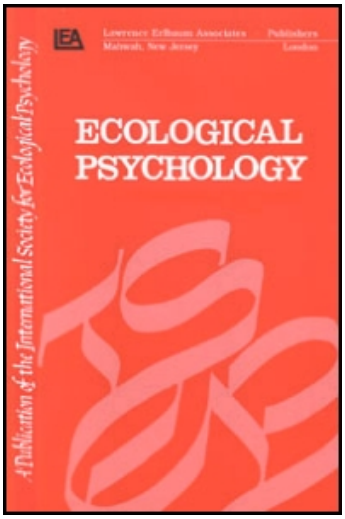

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The Calibration of Walking Transfers to Crawling: Are Action Systems Calibrated?

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Calibration is needed to scale actions appropriately. Earlier studies suggested that calibration transfers to actions that serve the same goal (Rieser, Pick, Ashmead, & Garing, 1995). This experiment further tested this functional hypothesis by asking whether the calibration of walking transfers to crawling. To recalibrate walking, participants walked on a treadmill for 15 min in a virtual environment in which the visual speed was faster than, equal to, or slower than the walking speed. After each of these rearrangement phases, the participants had to walk or crawl to a seen place without vision. The distance locomoted showed that the calibration of walking generalized to crawling, which supports the functional hypothesis. It is suggested that action systems are calibrated.

Movements must be appropriately scaled to the environment for behavior to be successful. Calibration contributes to the establishment and maintenance of such scaling (e.g., Adolph & Avolio, 2000; Bingham, Zaal, Robin, & Shull, 2000; Mark,

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1987). We take the calibration of action to bear on the relation between information guiding a movement and the movement itself. Calibration is thereby to be distinguished from perceptual learning, or what Gibson (1966) called the *education of attention,* the process by which perceptual systems converge on the perceptual variable that specifies the to-be-perceived or to-be-acted upon property (e.g., see Jacobs, Michaels, & Runeson, 2000; Michaels & de Vries, 1998; Runeson, Juslin, & Olsson, 2000).

Calibration is presumably a continual process (e.g., see Bingham et al., 2000) and is explicitly required in situations that require an information–action relation to be adjusted for the action to be successful. This can be a task in which the perceptual consequences of actions are altered, for example, walking on a moving sidewalk or doing surgery while looking through a microscope. It can also be a situation in which the action capabilities of the animal, known as effectivities (Shaw & Turvey, 1981) change, but the change is not specified by the perceptual variable the animal exploits. Mark (1987), for instance, suggested that the information about the sit-on-ability and climb-on-ability is scaled to eye-height, rendering it necessary for the perceptual system to recalibrate when the leg length increases.

At present, there is no fully fledged theory of the calibration in perception–action. An important precursor to such a theory is establishing what is calibrated. A discovery in calibration research that is of interest in this regard is that calibration seems to transfer in a functionally specific way. Rieser, Pick, Ashmead, and Garing (1995) presented walkers with a discrepancy between their walking speed and the optically specified environmental speed, and found that after this "rearrangement phase" participants walked too far or not far enough, depending on rearrangement type, when asked to walk to a seen place without vision. Not only was walking recalibrated, but also sidestepping. The calibration, however, did not transfer either to throwing to a place or to turning in place. When, on the other hand, throwing to a place or turning in place was recalibrated, no transfer to walking was found. Hence, it seems that calibrations are functionally organized. This led Rieser et al. to propose a functional model of perception–action organization. This model holds that the calibration of an action transfers to actions that serve the same goal and have the same perceptual consequences. Rieser et al. added the criterion of actions having the same perceptual consequences because they believed that in the rearrangement phase the participant discovered the new covariation between the action and its perceptual consequences, and acted upon this in the posttest. Rieser et al. were, however, not specific about perceptual consequences, so it is hard to use this criterion to make predictions.

Recently, Bruggeman, Pick, and Rieser (2001) provided further evidence for this functional organization of calibration. They showed that when participants sitting on a turning carousel were asked to throw beanbags underhand to the opposite side of the carousel, the directional recalibration was seen not only with underhand throwing, but also with overhand throwing. Walking direction, however, was not recalibrated.

We know of no other studies addressing the functional model, so one of the goals of our article is to further test the transfer of calibration in a new task. Second, in the paradigms used to date, the transfer of calibration was always to an action performed by the same limbs as the calibrated action. If calibrations are functionally organized, there should also be a transfer of calibration to an entirely different coordinative movement pattern that involves other limbs but that, nevertheless, executes the same function. In the experiment reported here, the hypothesis of transfer to a different coordinative pattern serving the same function is tested. We asked whether there is a transfer of calibration from walking to crawling on one's hands and knees. Both actions serve the function of getting to a place, and, thus, the functional model would predict a transfer of calibration.

To test whether the calibration of walking to a place transfers to crawling to a place, we used a design in which a rearrangement phase was followed by a posttest. In the test phase, the participants were asked to walk or crawl to a seen place without vision. The rearrangement phase consisted of a situation in which there was a discrepancy between visually and biomechanically (proprioceptively) specified walking speeds. This was expected to induce a recalibration of the biomechanical activity and the optically specified distance walked (cf. Rieser et al., 1995). So, if the walking speed is faster than the environmental speed, the participants should walk too far during the posttest, and if the walking speed is less than the environmental speed, the participants should not walk far enough during the posttest. If such overshoots and undershoots occur in crawling as well as in walking, this would mean that the calibration of walking transfers to crawling.

Rieser et al. (1995) contrived the discrepancy between the walking speed and the optically specified speed by having people walk on a treadmill that was towed by a tractor. An alternative is to create such a discrepancy with simulated optics in virtual reality. The reason for using a virtual reality, in our case a Cave Automated Virtual Environment (CAVE), instead of a real environment, was twofold. First, we used a virtual environment because creating a discrepancy between the optically and biomechanically specified walking speeds is obviously easier in a virtual environment than in a real one. Second, we were interested in whether the CAVE is an effective research tool to study the calibration of action. The CAVE has proven to be a moderately, although not unequivocally, successful tool to study certain interceptive actions (Zaal & Michaels, in press).

METHOD

Participants

Six men and 6 women were paid a small fee for their participation in the experiment. The participants ranged from 19 to 30 years of age. All had normal or corrected-to-normal vision and were not told of the goal of the experiment.

Apparatus

To create a discrepancy between the walking and environmental speeds, an electric treadmill (Walker G64, which has a moving surface of 109 × 34 cm) was placed in the CAVE situated at SARA (Academic Computing Services Amsterdam) in Amsterdam. The CAVE is a three-dimensional virtual environment that consists of three walls and a floor (each approximately 3 × 3 m). The treadmill was positioned so that the participant was in the middle of the CAVE. The visually specified forward motion was created by moving a point of observation through one of the CAVE's virtual environments, the Grand Place of Brussels. Presentation was stereoscopic; that is, on each of the four projection surfaces (three walls and the floor), images intended for the right and left eyes were projected in alternation. The perceiver wore liquid crystal glasses; the left and right lenses were opened in synchrony with the projected images. The viewing angle of the glasses was 87°. This simulation was computed from photographs of the Place. The virtual environment was elevated such that its ground was specified to be the same height as the treadmill's moving surface. In our judgment, the simulation yielded a compelling sense of moving through a visual environment at a specific rate.

Design and Procedure

The experiment consisted of a control test and three rearrangement phases, each followed by a posttest. Prior to the control test, there was a short warm-up in which the participant tried to walk and to crawl to seen points without vision. When the participant built some confidence in doing this, we started with the control test, the details of which were identical to the posttest, described below.

In each rearrangement phase, the participants walked on the treadmill for a period of 15 min; they held onto its rail and were asked to pay attention to the surroundings. They walked in a straight line on the treadmill, but the visual input indicated that they walked ellipses with a long axis of 91 m and a short axis of 39 m in a counterclockwise direction. The three rearrangement phases comprised a biomechanically slower condition (walking speed of 3 km/hr, environmental speed of 13 km/hr); an equal condition (walking and environmental speed of 3 km/hr); and a biomechanically faster condition (walking speed of 6 km/hr, environmental speed of 3 km/hr). Immediately after the rearrangement phase, the participants covered their eyes with opaque goggles, and were guided by an experimenter to the first starting point of the posttest.

Each test phase (control or posttest) consisted of six walks and six crawls. An experimenter indicated with the tip of his right foot the target to which the participant was to locomote. The participants, standing or on all fours, were asked to view the target, cover their eyes with opaque goggles, and walk or crawl to the target over a carpeted surface. The participants were told that the tester would move as they started their approach so that the path would be clear. In the walking condition, they were instructed to place the tip of their left foot at the target; in the

crawling condition, the tip of their left middle finger was to be placed at the target. Participants wore gloves to prevent them from feeling the starting points and the target, which were marked by tape. In addition, they wore earplugs to reduce any acoustic information that might be available about locations. They were also equipped with kneepads to reduce discomfort caused by crawling. Because it was hard to put the kneepads on and take them off, they were worn during the whole experiment.

For each trial, we measured the distance from the starting point to the stopping point, as well as the lateral distance between the stopping point and the straight line from the starting point to the target. Because the participants were neither to be aware of their performance nor to receive any visual information while being tested, they were guided from the stopping point to the next starting point by the experimenter. To ensure that it was a perceptual rather than a memory task, different target distances were used. There were three target distances for the walks (6.5, 6.0, 5.5 m) and three for the crawls (3.0, 4.0, 5.0 m). The target distances for the crawls were shorter, again, to reduce any discomfort caused by crawling. Blocks of three crawls were alternated with blocks of three walks. Within each of the blocks, the order of the three target distances was randomized. After each test phase there was a 5-min break.

Half of the participants started with the biomechanically slower condition, followed by the equal condition, followed by the biomechanically faster condition; the other half started with the biomechanically faster condition, followed by the equal condition, followed by the biomechanically slower condition. Within each of these groups, half of the participants started each posttest with crawls, and the other half started with walks. The participants were explicitly asked not to count their steps.

RESULTS

Because different distances were walked and crawled on different trials, we computed the percentage overshoot and undershoot for each trial. We did this by subtracting the target distance from the actual distance locomoted and dividing by the target distance. Overshoots were thereby positive, and undershoots negative.

We looked first at the control test to examine how the participants were initially calibrated. The first line of Table 1 shows that there was a slight overshoot in both the walks and the crawls and that the variability was high.

The second through fourth lines of Table 1 present measures that should indicate whether there were recalibration effects in the walks and the crawls. The direction of these effects were as predicted; the higher the ratio of biomechanical speed to visual speed, the further the locomotion. To determine whether the recalibration effects were significant, we performed a repeated measures analysis of variance (ANOVA) on the signed distance error as a percentage of target distance, with rearrangement type (faster, equal, slower), task (walk, crawl), and trial as

TABLE 1
The Average Signed Distance Errors as a Percentage of Target Distance for the Control Test and the Three Rearrangement Types

	Activity			
	Walk		*Crawl*	
	M	*SD*	*M*	*SD*
Control	4.9	7.6	2.1	10.2
Biomechanically faster	13.0	10.6	4.9	9.5
Equal	8.7	10.7	4.0	14.1
Biomechanically slower	6.7	10.2	0.3	10.5

within factors. We found a significant main effect of rearrangement type, $F(2, 22) = 3.861, p < .05$, showing that the degree of target overshoot depended on condition. A post-hoc test (Tukey–Kramer) showed that participants locomoted significantly farther (an average of 5.5%) in the biomechanically faster condition than in the biomechanically slower condition.

The ANOVA also revealed that the overshoot was significantly greater (average of 6.4%) in walking than in crawling, $F(1, 22) = 9.256, p < .05$, showing that on average the walks were calibrated differently from the crawls. There was no significant main effect of trial, nor were there significant interaction effects. The absence of a significant interaction effect between task and rearrangement type, $F(2, 22) = 0.3347, p > .10$, suggests that there were no differences in calibration effects between walking and crawling. Unfortunately, the low power of the statistical test (.206) makes this interpretation tentative. As a further test of whether both walking and crawling were calibrated, we performed separate repeated measures ANOVAs on the walks and on the crawls, with rearrangement type (faster, equal, slower) as a within factor. We found significant main effects of rearrangement type both for the walks, $F(2, 142) = 16.006, p < .001$, and for the crawls, $F(2, 142) = 4.637, p < .05$. Post-hoc tests (Tukey–Kramer) showed that participants walked significantly farther in the biomechanically faster condition than in the equal and the biomechanically slower condition, and crawled significantly farther in the biomechanically faster condition than in the biomechanically slower condition (see Figure 1). On the basis of this additional evidence, we conclude that both walking and crawling were recalibrated and, thus, that the calibration of walking transfers to crawling.[1]

[1]Because the visual input specified that the participants walked ellipses through the simulated environment, there was also a discrepancy between the optically and biomechanically specified walking direction. One might also expect this discrepancy to lead to a directional recalibration of locomotion; that is, a recalibration in the angle diverged from the straight line from the starting point to the target. Recalibration, if it occurs, is to be expected not only between the control test and the recalibration phases, but also between the recalibration phases because of the different ratios of biomechanical to visual speeds. We computed the angles at which the participants diverged from the straight line from the

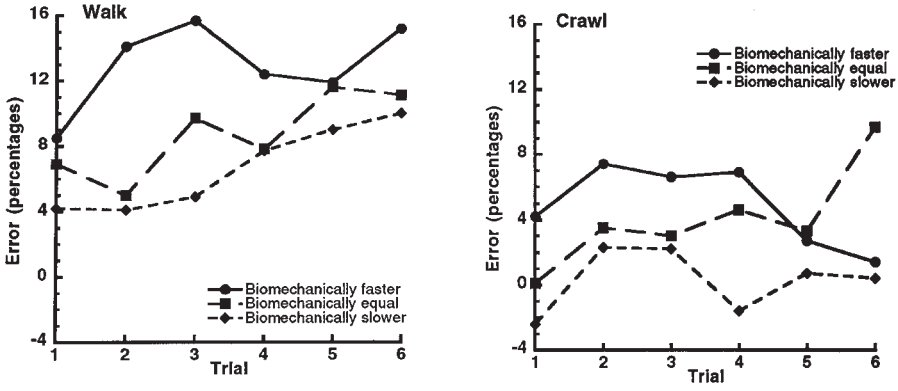

FIGURE 1 The average signed distance errors as a percentage of target distance for each trial of the three rearrangement types. The left figure depicts the walks, and the right figure depicts the crawls.

Table 2 presents results for individual participants; the data have been averaged over trials. These scores provide a more detailed picture of the interparticipant variation both in the relative sizes of the calibration effects in the crawls and walks and in the differences between the rearrangement types for the walks and crawls.

DISCUSSION

Calibration helps scale action and perception appropriately to the environment. Earlier studies (Bruggeman et al., 2001; Rieser et al., 1995) suggested that calibrations are functionally organized; that is, if an action is calibrated, other actions that serve the same goal are calibrated as well. This experiment further investigated this theory. We asked participants to walk on a treadmill in a virtual environment, where the treadmill speed and optically specified speed were sometimes different. Following this recalibration procedure, they had to walk or crawl to seen targets without vision. We asked whether walking was recalibrated and, if so, whether the calibration of walking to a place transferred to crawling to a place. We found both recalibration of walking and transfer to crawling. Thus, overall, the results provide further support for the functional hypothesis.

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starting point to the target. A repeated measures ANOVA on the these angles, with rearrangement type (control, faster, equal, slower), task (walk, crawl), and trial as within factors, revealed only a main effect of trial, $F(5, 20) = 2.686$, $p < .05$. The fact that there were no other main effects or interaction effects ($ps > .1$) indicates that there was no directional recalibration of locomotion. Note that the angular discrepancy varies dramatically over the ellipse; the point of observation is moving almost linearly in the middle of the long sides, but is quite curved on the short sides. Thus, this design does not provide a strong test of directional recalibration or its transfer.

TABLE 2
The Average Signed Distance Errors as a Percentage of Target Distance for Each Participant for the Control Test and the Three Rearrangement Types

	Activity							
	Walk				*Crawl*			
Participant	*Control*	*Biomechanically Faster*	*Equal*	*Biomechanically Slower*	*Control*	*Biomechanically Faster*	*Equal*	*Biomechanically Slower*
1	8.2	20.5	15.3	7.1	–8.7	1.6	31.6	4.4
2	8.2	7.9	4.3	–2.5	17.1	6.0	–7.7	–7.1
3	3.7	13.7	5.6	6.4	4.4	4.4	2.0	–0.6
4	–1.0	2.7	–0.4	1.4	–4.3	–5.7	–7.3	–5.4
5	1.9	11.2	9.4	0.3	–2.0	2.0	–2.7	–9.7
6	12.2	29.3	22.6	25.7	6.7	18.0	9.9	8.3
7	14.1	9.8	11.2	15.4	4.8	10.2	7.7	12.4
8	9.6	12.0	–0.6	2.4	–3.8	–9.2	–12.3	–14.3
9	–2.7	1.7	–2.2	4.3	0.7	1.0	0.1	7.2
10	–3.9	2.4	0.2	–3.7	6.3	11.1	11.0	3.0
11	5.4	26.9	22.8	4.7	–2.2	9.2	7.7	–6.9
12	2.5	17.5	15.8	18.7	5.7	9.9	8.7	11.8

Is the CAVE an Appropriate Tool to Establish Recalibration of Walking?

The differences in overshoot between the three ratios of optically specified speed and the actual walking speed suggest that the virtual environment created by the CAVE is an effective tool to induce recalibration effects. But are there alternative explanations of the overshoots we observed? One might hypothesize that the effects are aftereffects of biomechanical activity, as has been reported by Anstis (1995). After all, the participants walked further in the faster condition than in the slower and equal conditions, and the walking speed in the former condition was 3 km/h faster than in the latter two. We believe that this hypothesis can be eliminated on the basis of the study by Rieser et al. (1995), which showed that the overshoot in walking to a seen place after walking on a treadmill is not due to the biomechanical activity alone. In one of their experiments, participants were to walk on a stationary treadmill with their eyes either closed or open. An overshoot was found in the eyes open condition, but not in the eyes closed condition, showing that the overshoot is not an aftereffect of the biomechanical activity but is due to the discrepancy between the biomechanical and visual speeds. On the basis of this result, we concluded that the effects in the walks and the transfer to the crawls were due to a perceptual-motor calibration.

For the CAVE to be deemed a good research tool to study recalibration, however, it must also be the case that the perceptual-motor calibration is the result of the discrepancies between the walking and environmental speeds contrived in the

CAVE. The alternative is that participants perceived the stationary screen on which the street scene was projected or the pixel structure of the images, and that the differences in walking speeds between the conditions caused the recalibration effects to a stationary environment. As Rieser et al. (1995) showed, a perceptual-motor calibration can also be established if the optically specified environmental speed is zero. Assuming that the overshoots in walking to a seen place without vision are greater if the walking speed is faster, this might also account for the differences between the faster condition (walking speed of 6 km/h) and the slower and equal conditions (3 km/h in both conditions), and the absence of difference between the slower and equal conditions. Relatedly, this hypothesis is consistent with the absence of an undershoot in the biomechanically slower condition. However, we know of no evidence that perceivers can ignore the optic flow in a CAVE. In any case, further tests are needed to establish with certainty that the calibration effects were in fact affected by the different optical speeds.

On What Is Calibrated

What do transfer studies tell us about what is calibrated? The results to date appear to allow rejection of one characterization of calibration: the thesis that calibration is effector specific (e.g., see Anstis, 1995). The effector-specific thesis claims that in a situation that requires an action to be recalibrated, the calibration is specific to the effector by which the action is performed. Thus, according to this hypothesis, any action performed with the same effector should also show the consequences of the calibration. This thesis can explain the transfer from the calibration of walking to side stepping (Rieser et al., 1995), from the calibration of underhand throwing to overhand throwing (Bruggeman et al., 2001), and might even explain the transfer of calibration from walking to crawling, because the legs also play an important role in the latter (e.g., see Adolph, Vereijken, & Denny, 1998). Two findings are, however, inconsistent with this thesis: The calibration of walking did not transfer to turning in place and vice versa (Rieser et al., 1995). Therefore, it seems, calibration is not specific to effectors.

Instead, calibration appears to relate to functions, rather than to specific effectors. In the remainder of this article, we attempt to elaborate the functional model of Rieser et al. (1995). In particular, we explore the possibility that action systems are calibrated.

Are Action Systems Calibrated?

A theory of the calibration of action systems can be derived from Reed's (1982, 1988, 1996) concept of action systems. Reed argued that theories of motor systems do not have the potential of explaining the goal-directed activity of animals in their environments. Reed was inspired, first, by Gibson's (1966, 1979) theory of perceptual systems, which claimed that the detection of information entailed systems

larger and more diverse than the senses as classically conceived. A second inspiration was the Russian action theorists (e.g., Bernstein, 1967; Luria, 1973), who developed the concept of functional system. Following Bernstein, Reed argued that animals are in a disequilibrium with their environments and therefore act continually so as to meet their goals and needs. Actions, Reed asserted, are not triggered by stimuli or commands from the brain, as motor theorists might hold, but are regulated by perceptual information existing in the ambient array, which specifies both what the animal can do and how it can do it. Only by picking up such information can animals act adaptively in the environment.

Reed (1982, 1996) argued that in the course of evolution, selection pressures have given rise to systems that are each capable of performing a function. He termed these *action systems*. An action system should not be thought of as a specific collection of anatomical units that performs a particular function; instead, a characteristic of an action system is that it can accomplish its function by several means. For instance, the locomotion system of a human being, which performs the function of getting to a place, can perform its function by walking, crawling, side stepping, and so on. An action system is characterized by what Luria (1973) called a "mobility of its component parts" (p. 27): The task and the final result stay the same, but the way the function is performed and, thus, the anatomical parts involved may vary.

A theory of the calibration of action systems would hold that in a situation that requires actions to be rescaled, it is not the action that is calibrated, but the system that is capable of reaching the intended goal, the action system. Because an action system is capable of performing a function by several means, all such means are rescaled if the action system is calibrated. As an aside, note that the concept *transfer of calibration* would no longer be appropriate in this theory; transfer implies that one action is calibrated and that this calibration spreads out to other actions. If action systems are calibrated, then the calibration applies to (rather than transfers to) the various distinguishable ways of executing the function, such as walking or crawling.

The idea of the calibration of action systems predicts that if an action system is calibrated, all the means by which it can perform the function are rescaled. However, this idea requires elaboration on several fronts before it can make testable predictions. To make testable predictions, one must be able to enumerate the action systems that constitute an animal's behavioral repertoire, but at present, there are no unambiguous principles for doing so. Reed's (1982) claim that action systems are "the results of parallel or convergent evolution" (p. 113) does not suffice as a criterion to distinguish the systems, and the taxonomy he offered in his articles (1982, 1988) and book (1996) is, as he himself acknowledged, "provisional" (Reed, 1982, p. 114).

It is not clear what criteria should be used to distinguish the action systems. Here lies a potential role for calibration. It may be that transfer studies can be used to provide the taxonomy of action systems: One investigates actions to which a cal-

ibration applies and tries to reveal what the action system is on the basis of the results. Such a strategy, of course, precludes testing whether action systems are calibrated; it assumes that action systems exist and are calibrated independently. The results to date suggest, however, that this is a reasonable assumption. The finding that if walking to a place is recalibrated, crawling and side stepping are recalibrated as well, but throwing and turning in place are not, suggests that human beings have a locomotion system that can be calibrated. Such a system is presumably the kind of system Reed had in mind: It performs an evolutionarily important function and is able to achieve this function by several means. If further transfer studies reveal other such systems, the recalibration methodology may turn out to be a proper means by which the taxonomy of action systems can be established. Even though using transfer studies to distinguish the action systems renders the hypothesis that action systems are calibrated untestable, that strategy may further the understanding of the nature of action systems and yield hypotheses about calibration that are testable in other paradigms.

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